Recent Results from Belle

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The huge data sample accumulated at the KEKB storage ring allows for dedicated analyses in charm spectroscopy. A new, narrow resonance with a mass of 3.872GeV was found in decays of B mesons. Its properties remain unexplained. Results on various properties of the $\mathrm{D_{sJ}}(2317)$ resonances have been updated. Older results on the unexpectedly large cross section for double charmonium production in $\mathrm{e^+e^-}$ annihilation have been confirmed and a refined analysis is presented.

1. Introduction

Although known as a B-factory, the asymmetric storage ring KEKB enables the Belle detector to explore the charm sector. Charmed hadrons are not only the dominant decay product of b flavoured mesons, but, in addition, the decay kinematics give valuable constraints allowing the detection of previously unobserved particles and the determination of their quantum numbers.

Due to the excellent performance of the KEKB accelerator, the data sample available for charm studies at Belle is unprecedented. Over a year ago, KEKB reached its design luminosity of $\mathcal{L} = 10^{-34}/\mathrm{cm}^2/\mathrm{s}$ and since then shifted its instantaneous peak luminosity to $13.92\mathrm{nb}^{-1}\mathrm{s}^{-1}$. Until July 2004, Belle accumulated a total integrated luminosity of about 287 fb^{-1}. About 257 fb^{-1} was recorded at the $\Upsilon(4\mathrm{S})$ resonance, with the largest part of the remaining 29 fb^{-1} about 60 MeV below the resonance. In the following a few recent results from the Belle collaboration based on smaller data sets are presented, see [1] and references therein for more details on the analyses.

2. X(3872)

In decays of B mesons, the $b \to c\bar{c}s$ transition is of great importance due to the CKM matrix elements involved. Both vertices of the exchanged W boson carry the largest possible matrix elements for this decay. So, final states with double charm and charmonium states can be produced to a vast amount. For charmonium, B decays turn out to be a complementary testing field to the production of these states in $\mathrm{e^+e^-}$ annihilation at lower energies.

In general, two variables are commonly used for selecting fully reconstructed B candidates, i.e. candidates which while decay chain has been completely identified and reconstructed. Both make use of the fact that at this center-of-mass energy (CME), both B mesons are produced back-to-back with a well known energy, $E = \sqrt{s}/2$. One is the beam constrained mass $\mathrm{M_{bc}}$, where for the invariant mass of the B candidate, the energy of the candidate is replaced by the well known energy E : $\mathrm{M_{bc}} = \sqrt{E^2 - \vec{p}^{\,2}_{cand}}$. The other one is the energy difference $\Delta\mathrm{E} = E - E_{cand}$ between E and the energy of the B candidate.

Selecting $B^\pm \to \mathrm{J}/\Psi\pi^+\pi^-K^\pm$ decays by requiring $\mathrm{M_{bc}}$ of the B candidate to be within 5.271 GeV $< \mathrm{M_{bc}} <$ 5.289 GeV and the energy difference $\Delta\mathrm{E}$ to be within $|\Delta\mathrm{E}| <$ 30 MeV, a clear peak at around 600 MeV in the mass difference between the J/Ψ plus the $\pi^+\pi^-$ system and the J/Ψ can be identified with the $\Psi(3770)$. A second peak about 170 MeV higher than the one from the $\Psi(3770)$ can be seen. MC studies showed that this could not be produced by e.g. reflections of any known particle, see Fig. 1. It has therefore been attributed to a new particle, dubbed the X(3872), as it's measured mass is 3872.0 ± 1.0 MeV [2]. It's resolution has been determined to be less than the detec-

tor resolution for this channel of 2.3 MeV. The product branching ratio for $B^{\pm} \to$ X(3872)$K^{\pm}$ has been determined to $\mathcal{B}(B^{\pm} \to \mathrm{X}(3872)K^{\pm}) = (1.3{\pm}0.3){\times}10^{-5}$. Its large value suggests that the discovery channel is one of the, if not the dominant decay channel of the X(3872).

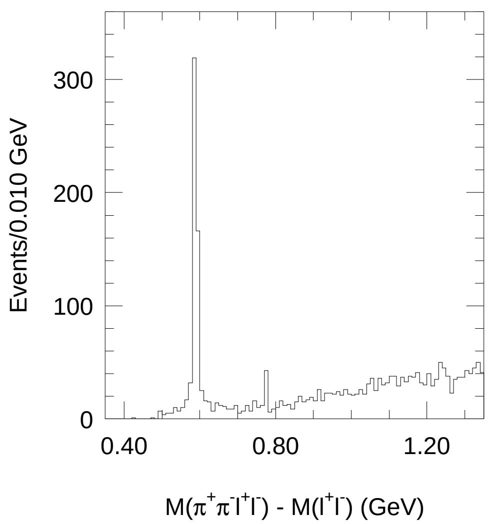

Figure 1. The mass difference between the J/$\Psi\pi^+\pi^-$ system and the J/Ψ itself. The large peak at 600 MeV is due to the decay of the Ψ(3770). The second, smaller peak at 770 MeV cannot be explained by any known particle and has been attributed to a new particle, called the X(3872).

Subsequently, the X(3872) was confirmed by CDF[3], D0[4] and BaBar[5]. Below, the mass and width measurements of the X(3872) for all four experiments are listed, together with its weighted average calculated from the first three experiments only as the BaBar result quotes only a total uncertainty. The D0 measurement has been transformed from $\Delta M(\pi^+\pi^-\mathrm{J}/\Psi - \mathrm{J}/\Psi)$ to $M(\mathrm{X}(3872))$ using the current world average of $M(\mathrm{J}/\Psi)$.

Exp.	mass [MeV]	width [MeV]
Belle [2]	$3872.0 \pm 0.6 \pm 0.5$	< 2.3
CDF [3]	$3871.3 \pm 0.7 \pm 0.4$	< det. res.
D0 [4]	$3871.8 \pm 3.1 \pm 3.0$	< det. res.
BaBar [5]	3873.4 ± 1.4	-
average	$3871.66 \pm 0.45 \pm 0.31$	-

Various two particle invariant masses do not exhibit a noticeable structure except the invariant mass of the $\pi^+\pi^-$ system, see Fig. 2. Similar

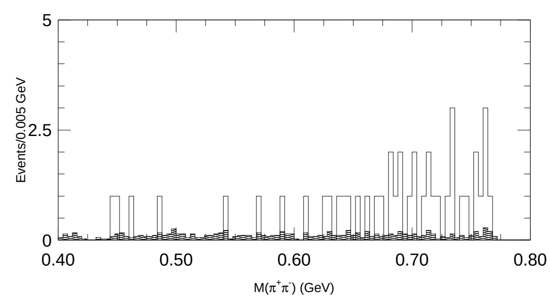

Figure 2. The mass distribution of the $\pi^+\pi^-$ system clusters at large values close to the kinematic limit. This suggests, it could originate from a ρ^0, which would constrain the C-parity of the new particle X(3872). The hatched histogram shows data from the sidebands.

to the corresponding distribution for the Ψ(3770), the dipion mass prefers larger values, close to the kinematic limit of around 770 MeV. It's distribution suggest, the dipion system could originate from a ρ^0. This would have the direct consequence of constraining the C-parity of the new particle. Would the dipion system actually be a ρ^0, the X(3872) must be a $C = +1$ state as $C = -1$ particle cannot decay into two $C = -1$ daughters. Furthermore, in this case, the decay into X(3872) $\to$ J/$\Psi\pi^0\pi^0$ would be forbidden. Results on this decay mode can be expected once more data is accumulated.

A second noticeable fact is the absence of the

decay of the X(3872) into $D\bar{D}$, a dominant decay for the considerably lighter $\Psi(3770)$. In decays of the form $B \rightarrow D\bar{D}K$ the following limit has been determined to be

$$\frac{\Gamma(\mathrm{X}(3872) \rightarrow D\bar{D})}{\Gamma(\mathrm{X}(3872) \rightarrow \pi^+\pi^-\mathrm{J}/\Psi)} < 7 \tag{1}$$

where the corresponding ratio for the $\Psi(3770)$ is

$$\frac{\Gamma(\Psi(3770) \rightarrow D\bar{D})}{\Gamma(\Psi(3770) \rightarrow \pi^+\pi^-\mathrm{J}/\Psi)} > 160. \tag{2}$$

This disfavours strongly an assignment of natural quantum numbers like 0^{++} or 1^{--} to this new state.

As the X(3872) decays into a charmonium state, it is plausible to consider it to be a charmonium as well. Grouping all reasonable charmonium candidates, i.e. candidates with a significantly large branching ratio into $\mathrm{J}/\Psi\pi^+\pi^-$, into groups depending on their C parity leaves 3 candidates for each possible parity assignment. These are the h_c', Ψ_2 and Ψ_3 for the $C = -1$ assignment and the η_c'', χ_c1' and η_c2 for the $C = +1$ assignment. In the following, it will be shown that the measured properties of the X(3872) disfavour all six possible charmonium assignments listed above. As for the Ψ_3, a large branching fraction into DD^* is expected. However, it has been argued, that the large angular momentum strongly suppresses this decay mode.

C-parity	Name	J^{PC}	spectroscopic name
	h_c'	1^{+-}	2^1P_1
C=-1	Ψ_2	2^{--}	1^3D_2
	Ψ_3	3^{--}	1^3D_3
	η_c''	0^{-+}	3^1S_0
C=+1	χ_c1'	1^{++}	2^3P_1
	η_c2	2^{-+}	1^1D_2

2.1. Is $C(\mathrm{X}(3872)) = -1$?

One obvious candidate for the X(3872) is the h_c', for which a sizable branching ratio into $\pi^+\pi^-\mathrm{J}/\Psi$ is expected and its predicted mass is rather close to the mass of the X(3872). Here, a distribution worthwhile to check is the angular distribution of the $\mathrm{K}^\pm$ in the rest frame of the X(3872) with respect to the flight direction of the J/Ψ in the rest frame of the X(3872) candidate. For the h_c' as well as any other 1^{+-} state, the distribution will be proportional to $\sin^2\theta$. However, the measured distribution shows clearly a different behaviour as indicated by the reduced χ^2 of $\chi^2/d.o.f. = 75/6$.

As for the Ψ_2 and Ψ_3, again, the measured $\pi^+\pi^-$ distribution does not agree with the expected distribution for these two particles. Additionally, for these particles, radiative decays into $\gamma\chi_{c1}$ and $\gamma\chi_{c2}$ would have branching ratios more than two and a half times larger or more than three and a half times larger than that of the discovery mode, respectively. However, no signal has been found and upper limits on the ratio of branching ratios have been determined to be

$$\frac{\mathrm{X}(3872) \rightarrow \gamma\chi_{c1}}{\mathrm{X}(3872) \rightarrow \pi^+\pi^-\mathrm{J}/\Psi} < 0.9 \tag{3}$$

and

$$\frac{\mathrm{X}(3872) \rightarrow \gamma\chi_{c2}}{\mathrm{X}(3872) \rightarrow \pi^+\pi^-\mathrm{J}/\Psi} < 1.1 \tag{4}$$

respectively. This rules out also these two assignments.

In conclusion, no good charmonium candidate with $C(\mathrm{X}(3872)) = -1$ is left.

2.2. Is C(X(3872))=+1 ?

This would mean that the $\pi^+\pi^-$ system is a ρ^0. However, the decay would be parity-violating and therefore strongly suppressed. Why the discovery channel has such a large branching ratio, would still have to be explained.

Here, the candidates are the η_c'', χ_c1' and η_c2.

The mass of the η_c'' is expected to be in the order of $\sim$ 4000 MeV, as it should be about approximately 40 MeV below its partner, the $\Psi(3S)$ with $m(\Psi(3S)) = (4040 \pm 2)$ MeV.

For the χ_c1', the radiative decay into $\gamma\mathrm{J}/\Psi$ is expected to dominate over the discovery channel. No signal is observed, strongly disfavouring this possible assignment.

For the η_c2, it is expected that the decay into $\eta_\mathrm{c2} \rightarrow \eta_c\pi^+\pi^-$ dominates over the discovery channel. However, the large branching ratio of the discovery channel would result in a extremely large branching ratio for this decay mode. This makes this assignment also very unlikely.

2.3. New Type of Matter?

One striking fact however remains: The mass of the X(3872) is within the small uncertainties identical to the sum of the masses of the D^0 and the D^{*0}. Many years ago such molecule-type bound states of mesons were predicted, see e.g. references in [2].

With more data, the nature of this new particle will be more explored.

3. $D_{sJ}(2317)$ and $D_{sJ}(2457)$

Over a year ago, more particles were discovered, which didn't fit well into the existing quark potential models. In e^+e^- annihilation, BaBar [6] claimed the discovery of a narrow state with a mass of 2317 MeV decaying into $D_s^+\pi^0$ and an unexplained excess in $D_s^+\pi^0\gamma$ around a mass of 2460 MeV. Later, CLEO [7] confirmed the first peak and established the second as another new particle decaying into $D_{sJ}(2457) \to D_s^{+*}\pi^0$, $D_s^{+*} \to D_s^+\gamma$. Belle then confirmed both particles and identified them also in decays of B mesons [8,9].

According to existing quark potential models, the masses of these two particles should be more than 50 MeV higher than the missing meson states containing $c\bar{s}$, the ${}^3P_0$ and the admixture of the ${}^1P_1$ and the ${}^3P_1$. The current world averages of these two new states are (2317.4 ± 0.9) MeV and (2459.3 ± 1.3) MeV, respectively.

Except for the too low masses, the other properties are in a good agreement with the expectation for these two $c\bar{s}$ candidates.

As both particles are too light to decay into DK and D*K, respectively, their dominant decay, assuming they are the missing $c\bar{s}$ states, will be the modes in which they have been discovered. Furthermore, the width of radiative and other decays are with the current, limited statistics, well in agreement with the theoretical expectations of Bardeen et al. [10] and by Godfrey [11]. Only one upper limit by CLEO on the ratio of $\frac{DsJ \to D_s^{+*}\gamma}{DsJ \to D_s^+\pi^0} < 0.06$ cannot be explained by above mentioned models. The only other upper limit on this ratio by Belle determined in decays of B mesons, is significantly weaker. Except for the discovery channels, only two other decay modes have been observed, both for the $D_{sJ}(2457)$. These are $D_{sJ}(2457) \to D_s^+\gamma$ seen by Belle in both B decays (0.38 ± 0.13) and in e^+e^- annihilation (0.55 ± 0.15) as well as by BaBar in B decays only (0.38 ± 0.12). Latter one is the weighted average over various B decay modes. The other observed decay mode of the $D_{sJ}(2457)$ is the decay $D_{sJ}(2457) \to D_s^+\pi^+\pi^-$ with an relative branching ratio of (0.14 ± 0.05) w.r.t. to discovery channel, observed in e^+e^- annihilation by Belle. This number slightly, i.e. with a significance of about 1 σ, disagrees with the two upper limit set by Belle in B decays (< 0.10) and by CLEO (< 0.08). Other upper limits on decay modes are also in the (10-60)% order, and agree rather well with the predictions.

For the lighter $D_{sJ}(2317)$, only predictions for the decay $D_{sJ}(2317) \to D_s^{+*}\gamma$ exist. Here, the prediction by Bardeen is closer to the stringent limit by CLEO mentioned above, the prediction by Godfrey is higher by a factor of three. Experimentally, two more upper limits for decays of the $D_{sJ}(2317)$ have been determined, however, no theory predictions for these two modes exist. These two decay modes are $D_{sJ}(2317) \to D_s^+\gamma$ and $D_{sJ}(2317) \to D_s^+\pi^+\pi^-$, which are forbidden for the missing $c\bar{s}$ states. Stringent limits in the percent or even the permille level support the hypothesis, this particle is in fact the so far unobserved $c\bar{s}$ state.

More information about the spin of an particle can be derived from angular distributions like helicity distributions, decay angle distributions in the rest frame of the mother particle w.r.t. the flight direction of the mother in the rest frame of the B.

For the $D_{sJ}(2317)$ the helicity angle distribution for the decay $D_{sJ}(2317) \to D_s^+\pi^0$ is in excellent agreement with the spin 0 hypothesis .

Also for the $D_{sJ}(2457)$, the helicity angle distribution in $D_{sJ}(2457) \to D_s^+\gamma$ supports the spin 1 assignment of this particle, likely being the so far missing $c\bar{s}$ state .

In conclusion, the new discovered particle, named the $D_{sJ}(2317)$ and the $D_{sJ}(2457)$, behave like the unobserved $c\bar{s}$ states, however their masses are significantly too low.

4. Double $c\bar{c}$ production

Another very nice and elegant analysis showing surprising results is the investigation about the double $c\bar{c}$ production. Here, a J/Ψ is reconstructed in the very clean lepton channel, then, simply, its recoil mass is plotted. The effects of ISR photons are taken into account, see [12,13] for details. A momentum cut removes contribution from decays of B mesons.

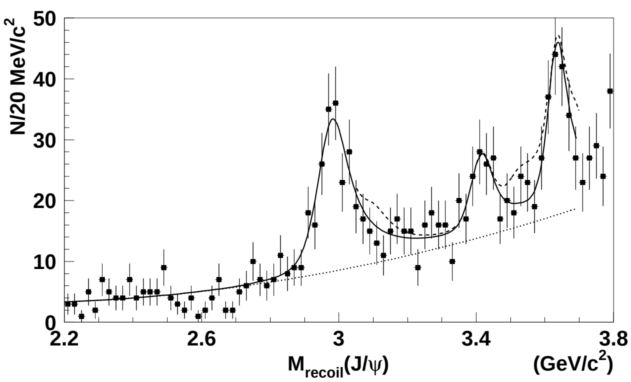

Figure 3. The recoil mass spectrum against a fully reconstructed J/Ψ in e^+e^- annihilation events. A clear enhancement of activity above the $c\bar{c}$ threshold is visible, in contrast to predictions by NRQCD.

The recoil mass spectrum does not reveal a large signal until about 3 GeV, the charm production threshold, where the signal strongly increases.

Zooming into the threshold region, see Fig. 3, reveals three clear distinct peaks, in a previous analysis [12] identified with the η_c, χ_{c0} and the η_c(2S). The masses of these particles were consistent with the world average. For the η_c(2S), it was only the second observation. Note, that e.g. the production of two J/Ψ from a single γ is forbidden by conservation of C-parity.

Another surprising result of the old analyses were that there is almost no activity below 3 GeV, but a very strong activity above.

So far, the only theory predicting cross sections of charmonium production at this center-of-mass energy is non-relativistic QCD, NRQCD for short. It predicts the J/Ψgg production to be dominant with a total cross section of about $\sim$ 1 pb. The colour singlet production of J/Ψg might dominate the phase space as a quasi two body decay at the endpoint with up to $\sim$ 0.5 pb. Double $c\bar{c}$ production via gluon splitting into $c\bar{c}$ is expected to be suppressed by about a factor of 10-20 w.r.t. to J/Ψgg.

The measurement however finds the J/Ψgg process to be negligible and the double $c\bar{c}$ production dominates with about 80%. The total cross section for double $c\bar{c}$ production is about one order of magnitude too large compared to the prediction of NRQCD.

Several, alternative explanations arose, e.g. that under the η_c peak, significant contribution from $e^+e^- \rightarrow \gamma\gamma \rightarrow$ J/ΨJ/Ψ could be hidden. Glueballs could interfere with the charmonium states and increase the cross section, or, a bias in the momentum scale can deteriorate any interpretation, that the first peak would no be due to the η_c.

In a refined analysis [**?**] performed on a larger data set of 155 fb^{-1}, the fit to the recoil mas spectrum now allowed for all narrow resonances in this mass region. To the η_c, χ_{c0}, η_c(2S) allowed in the previous analysis, the J/Ψ, $\chi_{c1(2)}$ and the $\Psi(2S)$ were added. However, the fitted yield for the last three particles was consistent with zero, even negative for the J/Ψ and the $\Psi(2S)$. As no signal was observed, the mass and width of these particles were fixed to their world average values. For the other three particles, these values were floated in the fit. The fitted yields are listed below

$c\bar{c}$	mass [MeV]	N	signif.
η_c	2972 ± 7	235 ± 26	10.7
J/Ψ	fixed	-14 ± 20	-
χ_{c0}	3407 ± 11	89 ± 24	3.8
$\chi_{c1(2)}$	fixed	10 ± 27	-
η_c(2S)	3630 ± 8	164 ± 23	5.3
$\Psi(2S)$	fixed	-26 ± 29	-

In order to confirm the peak around 3 GeV is caused by η_c and not by J/Ψ, various tests have been performed. First, about 230 signal events in the η_c mass region allow fully reconstruct a few events. The $\eta_c$was reconstructed in the $\eta_c \rightarrow K^0_S K^+ \pi^-$ and the $\eta_c \rightarrow 2(K^+K^-)$ decays. From Monte-Carlo, 2.6 events were expected to be reconstructed. In the data, 3 events have been observed, in excellent agreement with the expectation. Additionly, in the dilepton channel of the J/Ψ no event events has been observed, in accordance with the expectation.

Furthermore, an angular analysis of the production and helicity angle distribution for the reconstructed J/Ψ have been performed for all events in the three signal peaks. For the production via $e^+e^- \rightarrow \gamma^* \rightarrow J/\Psi c\bar{c}$, due to conservation of angular momentum of the exchanged γ^*, the production and the helicity angle distributions have to be equal. For processes like $e^+e^- \rightarrow \gamma\gamma \rightarrow J/\Psi c\bar{c}$ no such constrain exist.

All distributions have been fitted with a function of the form $f(x) \sim 1+\alpha\cos^2\theta$ with α floated. Within large uncertainties, the results are consistent with the hypothesis of a 1 γ exchange. The last column in the table below actually assumes the production via the 1 γ exchange, reducing slightly the uncertainty on α. Also listed in the last row are the predictions for a glueball.

	α_{prod}	α_{hel}	$\alpha_{prod} = \alpha_{hel}$
η_c	$1.4^{+1.1}_{-0.8}$	$0.5^{+0.7}_{-0.5}$	$0.93^{+0.57}_{-0.47}$
χ_{c0}	$-1.7^{+0.5}_{-0.5}$	$-0.7^{+0.7}_{-0.5}$	$-1.01^{+0.38}_{-0.33}$
η_c(2S)	$1.9^{+2.0}_{-1.2}$	$0.3^{+1.0}_{-0.7}$	$0.87^{+0.86}_{-0.63}$
G(0^+)	-0.9	-0.9	

Additionly, the cross sections for the production of double charmonium have been determined. The results are listed in the table below. Note, that for the decay of the charmonium accompanying the J/Ψ, two or more charged particles were required in the analysis, reducing the visible cross section and therefore enhancing even more the discrepancy between theory prediction and experiment.

$c\bar{c}$	$\sigma_{Born} \times \mathcal{B}(c\bar{c} \rightarrow \geq 2\text{charged})[fb]$
η_c	$25.6 \pm 2.8 \pm 3.6$
J/Ψ	< 9.1
χ_{c0}	$6.4 \pm 1.7 \pm 1.0$
$\chi_{c1(2)}$	< 5.3
η_c(2S)	$16.5 \pm 3.0 \pm 2.5$
$\Psi(2S)$	< 13.3

5. Conclusion

Over the last years, the b-factories made several new unexpected discoveries, mostly involving charmed mesons. An apparent charmonium state, the X(3872), does not fit at all into the charmonium spectrum. It might represent a new form of matter, a molecule build out of mesons. Other new discovered particles in the $c\bar{s}$ system behave like expected, however, their masses are significantly too low. And last, but not least, the production cross section of double charmonium in e^+e^- annihilation is still about an order of magnitude larger than predicted by theory.

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